Characterization of Quasi-Optical NbN Phonon-cooled Superconducting HEB Mixers

Ling Jiang, Wei Miao, Wen Zhang, Ning Li, Zhen Hui Lin, Qi Jun Yao, Sheng-Cai Shi, Sergey I. Svechnikov, Yury B. Vakhtomin, Sergey V. Antipov, Boris M. Voronov, Natalia S. Kaurova, and Gregory N. Gol'tsman

Abstract—**In this paper, we thoroughly investigate the performance of quasi-optical NbN phonon-cooled superconducting hot-electron bolometer (HEB) mixers, cryogenically cooled by a close-cycled 4-K refrigerator at 500 GHz and 850 GHz. The uncorrected lowest receiver noise temperatures measured are 800 K at 500 GHz without anti-reflection coating, and 1000 K @ 850 GHz with a 50 μm thick Mylar anti-reflection coating. The dependence of receiver noise temperature on the critical current and bath temperature of HEB mixer is also investigated here. Lifetime of quasi-optical superconducting NbN HEB mixers of different volumes, room temperature resistances, and critical temperatures are thoroughly studied. Increased room temperature resistance with time over the initial resistance changes between 1 and 1.2, and the reduced critical current with time over the initial value fluctuates slightly around 0.7 for most HEB mixers even of different volumes, room temperature resistances, and critical temperatures. The critical current degrades sharply while room temperature resistance varies over 1.25.**

***Index Terms*—Superconducting HEB mixer, noise temperature, anti-reflection coating, bath temperature, critical current, lifetime, room temperature resistance.**

I. Introduction

In recent decades, phonon-cooled superconducting hot electron bolometer (HEB) mixers have developed as the most sensitive heterodyne detector in the THz region. The double sideband (DSB) receiver noise temperature of phonon-cooled NbN superconducting HEB mixers has approached eight times the quantum limit ($8h\nu/k$) [1] and the required LO power is only tens of nanowatts.

To develop this heterodyne receiver technology for real astronomical and atmospheric observations, which usually require long-period operation, we have concentrated on the performance characterization of phonon-cooled NbN superconducting HEB mixers with a close-cycled 4 K refrigerator. It has been indeed demonstrated that although being with an ultra-thin NbN film (~3.5 nm), phonon-cooled NbN superconducting HEB mixers can survive the mechanical vibration and temperature fluctuation of 4-K close-cycled cryocoolers (GM two-stage type) [2]. In this paper, we measure the receiver noise performance of quasi-optical NbN superconducting HEB mixers at 500 GHz and 850 GHz with an anti-reflection coating. The dependence of receiver noise temperature on the critical current and bath temperature is also investigated. To obtain reliable operation of superconducting NbN HEB mixer with 4-K close-cycled refrigerator, it is also crucial to investigate the lifetime of NbN HEB mixers. The reduction of critical current with time as a function of the increase of room temperature resistance is demonstrated for different HEB mixers.

II. Measurement Setup

The measured quasi-optical NbN superconducting HEB mixer chip was fabricated in Moscow State Pedagogical University (MSPU), as shown in Fig. 1. The ultra-thin (3.5 nm) NbN superconducting film bridge is contacted to the spiral antenna by the two sides contact pads. The RF and LO signals are coupled to the ultra-thin NbN superconducting film bridge through the log - spiral antenna, where mixing happens.

An IR filter made of two layers of Zitex A155 [3] on the 40-K shield of the 4-K cryostat is used to block the IR thermal radiation into HEB mixer. The quasi-optical NbN superconducting HEB mixer chip was glued onto the flat surface of a hyper-hemispherical silicon lens of a diameter of 12 mm, which was adopted to focus the RF and LO signals to the log-spiral antenna. The hyper-hemispherical silicon lens with the superconducting HEB mixer chip was then put into a copper mixer block, which includes a 50-Ω coplanar waveguide transmission line with one port connected to the HEB mixer chip (via silver paste) and the other to the IF and DC output port. To further reduce IR thermal radiation into the superconducting HEB mixer, we used a copper shield to cover the whole mixer block. The shield indeed had a window of 25 mm diameter covered with a layer of Zitex G104 for RF and LO signal coupling. The whole mixer block and the 4-K shield

Manuscript received May 30, 2006. This work was supported by the NSFC under Contracts No. 10390163 and No. 10211120645, the CAS under Contract No. KJCX2-SW-T2, and the RFBR under Contract No. 04-02-39016.

L. Jiang, W. Miao, W. Zhang, N. Li, Z. H. Lin, Q. J. Yao, are with Purple Mountain Observatory, NAOC, Graduate University of Chinese Academy of Sciences, Nanjing, China. S. C. Shi is with Purple Mountain Observatory, NAOC, CAS, Nanjing, China. Phone: 86-25-83332203; fax: 86-25-83332206; e-mail: l.jiang@mwlab.pmo.ac.cn.

S. I. Svechnikov, Y. B. Vakhtomin, S.V. Antipov, B. M. Voronov, N.S. Kaurova, and G. N. Goltsman are with Department of Physics, Moscow State Pedagogical University, Moscow, Russia

were both mounted on the 4-K cold plate of the close-cycled cryostat.

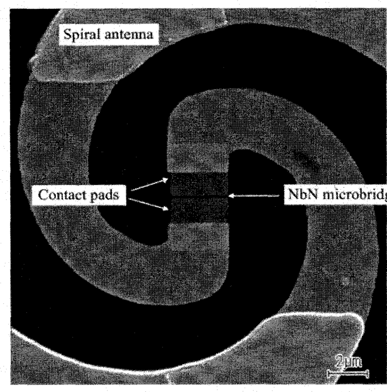

Fig. 1 Photograph of the measured quasi-optical NbN superconducting HEB mixer chip. The HEB device consists of the NbN microbridge and two contact pads in either side. Au spiral antenna is deposited in the outer layer.

We used the conventional Y-factor method to measure the noise performance of the quasi-optical NbN superconducting HEB mixer. The schematic of measurement setup is displayed in Fig. 2. A beam splitter made of a 15-μm thick Mylar film [4] was employed to couple the RF and LO signals into the vacuum window (15-μm thick Mylar film) of the 4-K cryostat. The RF signal was from a chopper, indeed a 295-K and 77-K blackbody. The 500- and 850-GHz LO source was provided by a BWO (backward wave oscillator). The IF output signal of the quasi-optical superconducting HEB mixer went through a bias-tee, a 0.8-2 GHz cooled HEMT low noise amplifier (of 36-dB gain) and a room-temperature amplifier (of 45-dB gain), a bandpass filter (1.5±0.055 GHz), and was finally measured by a square-law detector of a sensitivity of 1 mV/μW.

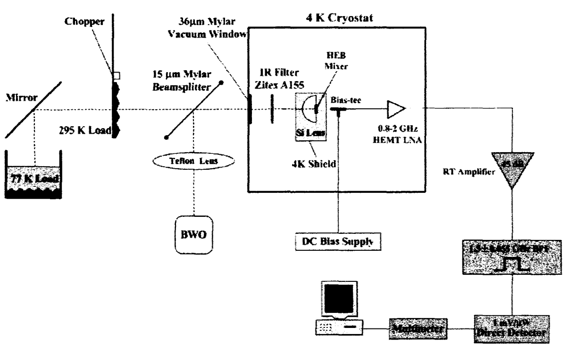

Fig. 2 Schematic of the receiver noise temperature measurement setup.

III. Measurement Results

A. Receiver noise temperature measurement at 500 and 850 GHz

We measured the receiver DSB noise temperature at 500 and 850 GHz. The uncorrected lowest receiver noise temperature measured at 500 GHz is 800 K without an anti-reflection coating, as shown in Fig. 3. The optimum operating point is located in V_{bias}=1mV, I_{bias}=34μA.

In order to further reduce the receiver noise temperature, we cover a Mylar anti-reflection coating on the surface of hemispherical Si lens to decrease the impedance mismatching between Si lens and free space. The optimum thickness of Mylar film ($\varepsilon_{Mylar} \approx \sqrt{\varepsilon_{Si}}$) was chosen as 50 μm at 850 GHz. Fig. 4 shows the receiver noise temperature for different LO pumping levels and dc biases at 850 GHz. The lowest receiver noise temperature was measured 1000 K @ 850 GHz. The receiver noise temperature is reduced by 30% compared that without anti-reflection coating.

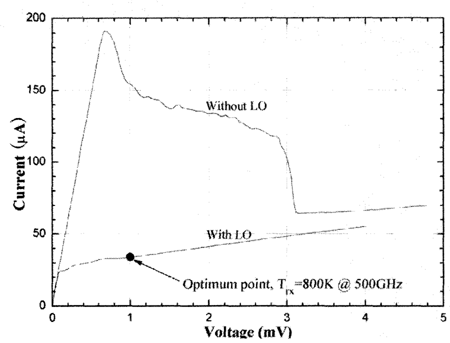

Fig. 3 Receiver noise temperature measured is 800 K at 500 GHz without an anti-reflection coating.

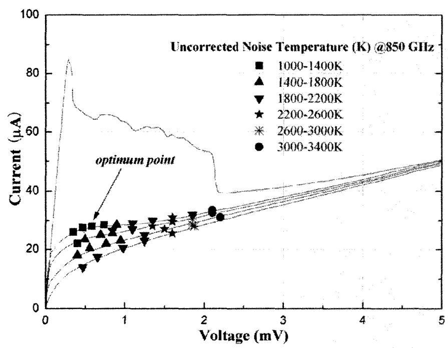

Fig. 4 Receiver noise temperature was measured for different LO pumping levels and dc biases at 850 GHz with a 50-μm thick Mylar film as anti-reflection coating. The lowest receiver noise temperature measured was 1000 K at 850 GHz.

B. Receiver noise temperature vs. critical current and bath temperature

Dependence of the receiver noise temperature on critical current and bath temperature was also investigated at 500 GHz. The HEB mixer has a width of 2.4 μm, length of 0.2 μm, and critical temperature of 9.4 K. Fig. 5 shows the IV curves and measured receiver noise temperatures for different critical currents. Note that the Si hemispherical lens wasn't covered by an anti-reflection coating. It is clearly that the receiver noise temperature deteriorates with the reduction of critical current. The HEB mixer temperature at different critical currents can be estimated from the following equation [5]

$$I_c(T) = I_c(0) * \left[1 - \left(\frac{T}{T_c}\right)^2\right] * \left[1 - \left(\frac{T}{T_c}\right)^4\right]^{0.5} \qquad (1)$$

Its validity has been successfully checked. Fig. 6 exhibits the receiver noise temperature and mixer critical current change with HEB mixer bath temperature. Below bath temperature of 5.6 K, the receiver noise temperature change very slowly. However, while the bath temperature increases beyond 5.6 K, the receiver noise temperature deteriorates sharply. We also measured another HEB device, which shows similar variation rule. The lowest HEB mixer temperature (i.e., 5.2 K) is 1 K larger than liquid helium temperature 4.2 K due to the bad thermal conductance between the mixer block and cold plate of the 4-K cryostat.

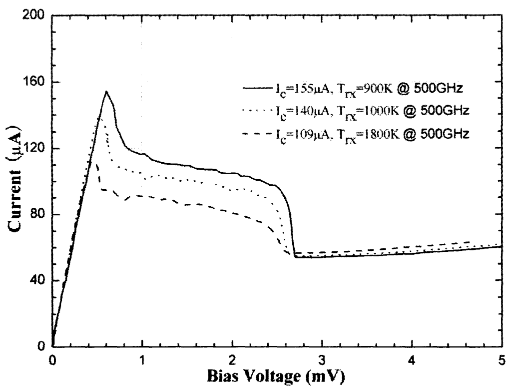

Fig. 5 IV curves and measured receiver noise temperature for different critical currents at 500 GHz without an anti-reflection coating.

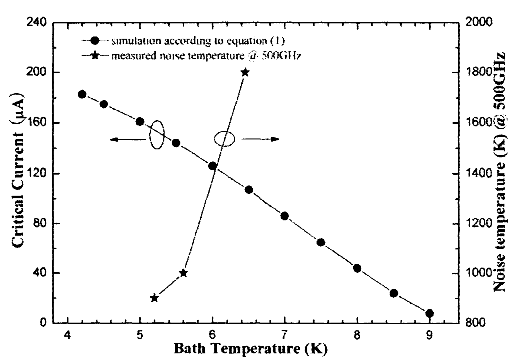

Fig. 6 Mixer critical current and receiver noise temperature measured at 500 GHz as a function of mixer bath temperature. The HEB device has width=2.4 μm, length=0.2 μm, T_c=9.4 K. circle symbol is obtained from equation (1).

C. Lifetime of superconducting HEB mixer

Lifetime of NbN HEB mixers have been investigated by M. Hajenius etc. [6], which indicates the standard HEB devices without passivation layer have a 15% increase in room temperature resistance and a 30% reduction in critical current about half a year after fabrication. We measured the variation of mixer room temperature resistance vs. that of critical current at an interval for these standard NbN HEB devices deposited in Si substrate of different volumes, room temperature resistance, and critical temperatures, as shown in Fig. 7. The room temperature resistance and critical current were measured, respectively in 10 days and 500 days after fabrication. The variation of room temperature resistance (characterized by $R_{300K,\ 500\ days}$ / $R_{300K,\ 10\ days}$) changes mainly from 1 to 1.2, and critical current fluctuates slightly around 0.7 (defined by $I_{c,\ 500\ days}$ / $I_{c,\ 10\ days}$) for most HEB devices even of different volumes, room temperature resistances, and critical temperatures. Furthermore, the critical current deteriorates strongly with the room temperature resistance changes beyond 1.25.

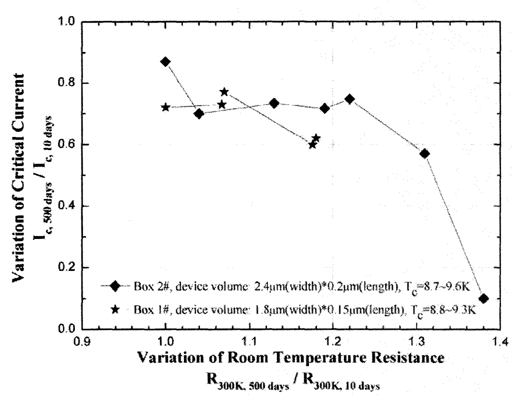

Fig. 7 Variation of critical current vs. room temperature resistance for different HEB devices at an interval, indicated in 10 and 500 days after fabrication. For most HEB devices of different volumes, room temperature resistance, and critical temperatures, the increased room temperature resistance over initial resistance varies from 1 to 1.2 and the reduced critical current over initial one fluctuates slightly around 0.7. The critical current deteriorates sharply with the further increment of normal resistance beyond 1.25.

IV. Conclusion

We have thoroughly investigated the receiver DSB noise temperature of quasi-optical phonon-cooled NbN superconducting HEB mixer, which is cooled by a 4-K close-cycled refrigerator. The measured lowest receiver DSB noise temperatures are 800 K at 500 GHz without anti-reflection coating and 1000 K at 850 GHz with a 50-μm thick Mylar anti-reflection coating. The receiver noise temperature changes inversely with the critical current, and the receiver DSB noise temperature is found to deteriorate strongly beyond bath temperature of 5.6 K. Increased room temperature resistance over initial resistance varies from 1 to 1.2 for most HEB devices of different volumes, room temperature resistances, and critical temperatures, and the reduced critical current over initial one fluctuates slightly around 0.7. While the room temperature resistance varies beyond 1.25, critical current deteriorates strongly.

V. Acknowledgment

We are very grateful to X. F. Shen, D.R. Yang, Q. G. huang, and S. H. Chen of PMO for technical support.

References

[1] J. J. A. Baselmans, M. Hajenius, J. R. Gao, T. M. Klapwijk, P. A. J. de Korte, B. Voronov, and G. Gol'tsman, "Doubling of sensitivity and bandwidth in phonon cooled hot electron bolometer mixers," *Applied Physics Letts.*, vol. 84, no. 11, pp. 1958-1960, 2004.

[2] L. Jiang, J. Li, W. Zhang, Q. J. Yao, Z. L. Lin, S. C. Shi, Y. B. Vachtomin, S.V. Antipov, S. I. Svechnikov, B. M. Voronov, and G. N. Goltsman, "Characterization of NbN HEB mixers cooled by a close-cycled 4 Kelvin refrigerator," *IEEE Trans. Applied Supercond.*, vol. 15, no. 2, pp. 511-513, June 2005.

[3] *ZITEX 100% PTFE Membranes*, Saint-Gobain Performance Plastics Corp., France.

[4] *Mylar Polyester Films*, Dupont Corp., USA.

[5] S. Cherednichenko, M. Kroug, H. Merkel, E. Kollberg, D. Loudkov, K. Smirnov, B. Voronov, G. Gol'tsman, , E. Gershenzon, "Local oscillator power requirement and saturation effects in NbN HEB mixers," *Proc. of 12th International Symposium on Space Terahertz Technology*, pp. 273-285, 2001.

[6] M. Hajenius, Z. Q. Yang, J. J. A. Baselmans and J. R. Gao, "Lifetime of NbN Hot Electron Bolometer Mixers," *Proc. of 16th International Symposium on Space Terahertz Technology*, pp. 217-221.